Mapping *Cladophora* Extent in Lake Michigan Using Multi-scale Satellite Imagery

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Cladophora Study: Goal and Objectives

- Overall goal
  - Quantify the role of remote sensing in mapping, monitoring, and managing *Cladophora* growth in the Great lakes
- Specific objectives
  - Quantify ability of Landsat, MODIS, and MERIS and commercial satellites to first map *Cladophora* extent and then characterize biomass based on observed depth corrected reflectance values
    - Quantify
      - maximum depth
      - seasonal performance
      - annual variability
      - best satellite bands
      - optimum depth correction (ratio vs. extinction coefficient)
      - optimum satellite viewing geometry
  - Used two locations (Sleeping Bear, MI, USA and Pickering Nuclear Power Plant, Ontario, Canada) to demonstrate initial feasibility of technique

The *Cladophora* Problem

- *Cladophora* is a native, filamentous, green alga that grows attached to solid substrate in all of the Laurentian Great Lakes (sparse in Lake Superior).
- Becomes detached after significant storm events and washes up on nearby beaches.
- Avian botulism outbreaks in northern Lake Michigan associated to large deposits of detached washed up *Cladophora.*
- Was a problem in the 1970s due to high levels of phosphorus.
- Great Lakes Water Quality Agreement management strategies helped to reduce phosphorus loadings to lessen nuisance *Cladophora* growth.
- Nuisance growth has become an increasing problem over the past decade due mostly to the arrival of invasive mussel species.
- More light is able to reach deeper allowing *Cladophora* to grow
- Mussel “colonies” create areas of hard substrate where *Cladophora* can grow.

Cladophora Mapping Algorithm

- Assuming uniform inherent optical properties, a depth corrected radiance algorithm arises, of the form:
- log-transformed radiance, Xj = $\ln(L-L_s)$
- L = Upwelling radiance
- L_s = Upwelling radiance in water of 'infinite' depth
- Eliminates radiance due to the water column, leaving upwelling radiance due to bottom component.
- Values less than zero indicate optically deep water signature.
- Adapted from Lyzenga et. al., 1978, 1981, 2006.
- Based on upwelling radiance detected by sensor
- The Depth Invariant Index uses multiple depth corrected radiance band inputs along with the specific diffuse attenuation coefficients (**Kd**) to solve a linear model for multiple bottom types

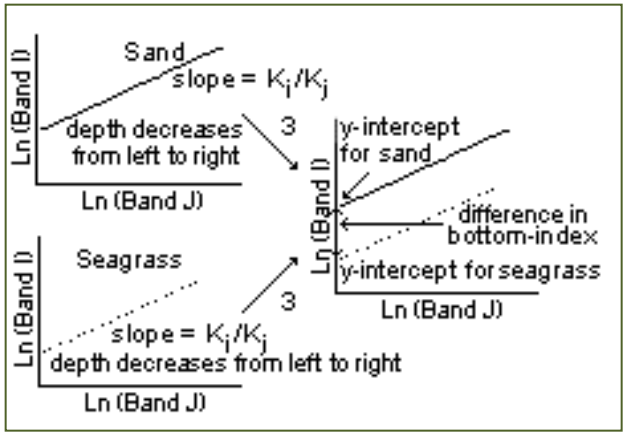
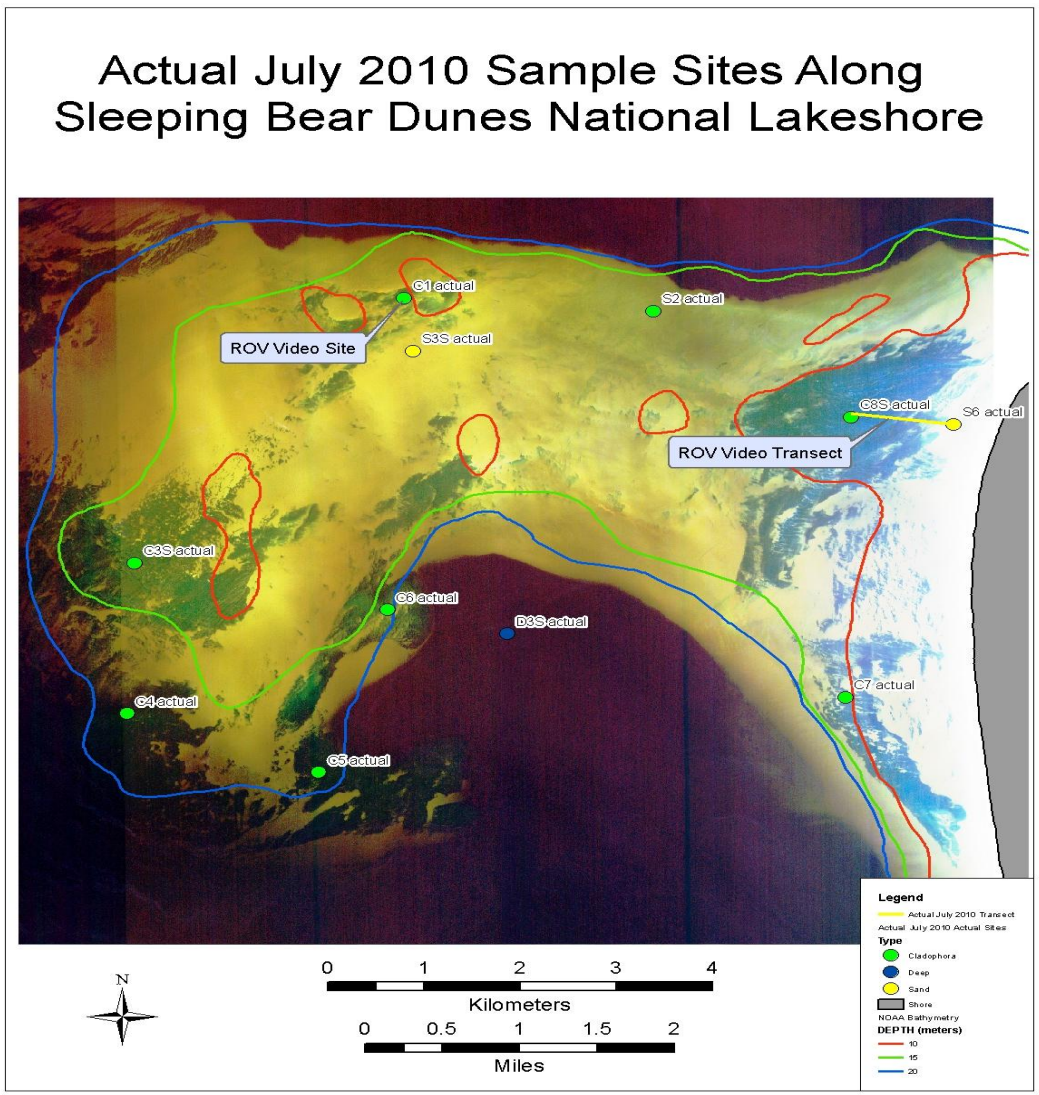


Figure displays scatter plot of depth corrected satellite bands and distinct parallel lines indicating different bottom types. *Image from* http://www.unesco.org/csi/pub/source/rs10.htm

Cladophora Study: 2009-2010 Field Activity (Sleeping Bear)

- Acquired imagery to guide sampling sites
- Overlaid image with depth and bottom substrate
- Based on depth, rock versus sand and radiance values classified image as sand, dense *Cladophora*, moderate *Cladophora*, or deep water
- Test area truthing: Sampled 19 sites
  - At most sites sampled:
    - location (GPS)
    - depth
    - secchi disk
    - diver observations
    - diver photos
    - diver collected *Cladophora* or sand sample
    - YSI water properties (temp, pH, conductivity, turbidity, and DO) as a function of depth (profile of water column)
    - ROV video, temperature, and side scan sonar
    - ASD spectro-radiometer measurements of bottom samples as well as detached floating *Cladophora*
    - dry weights of *Cladophora* samples

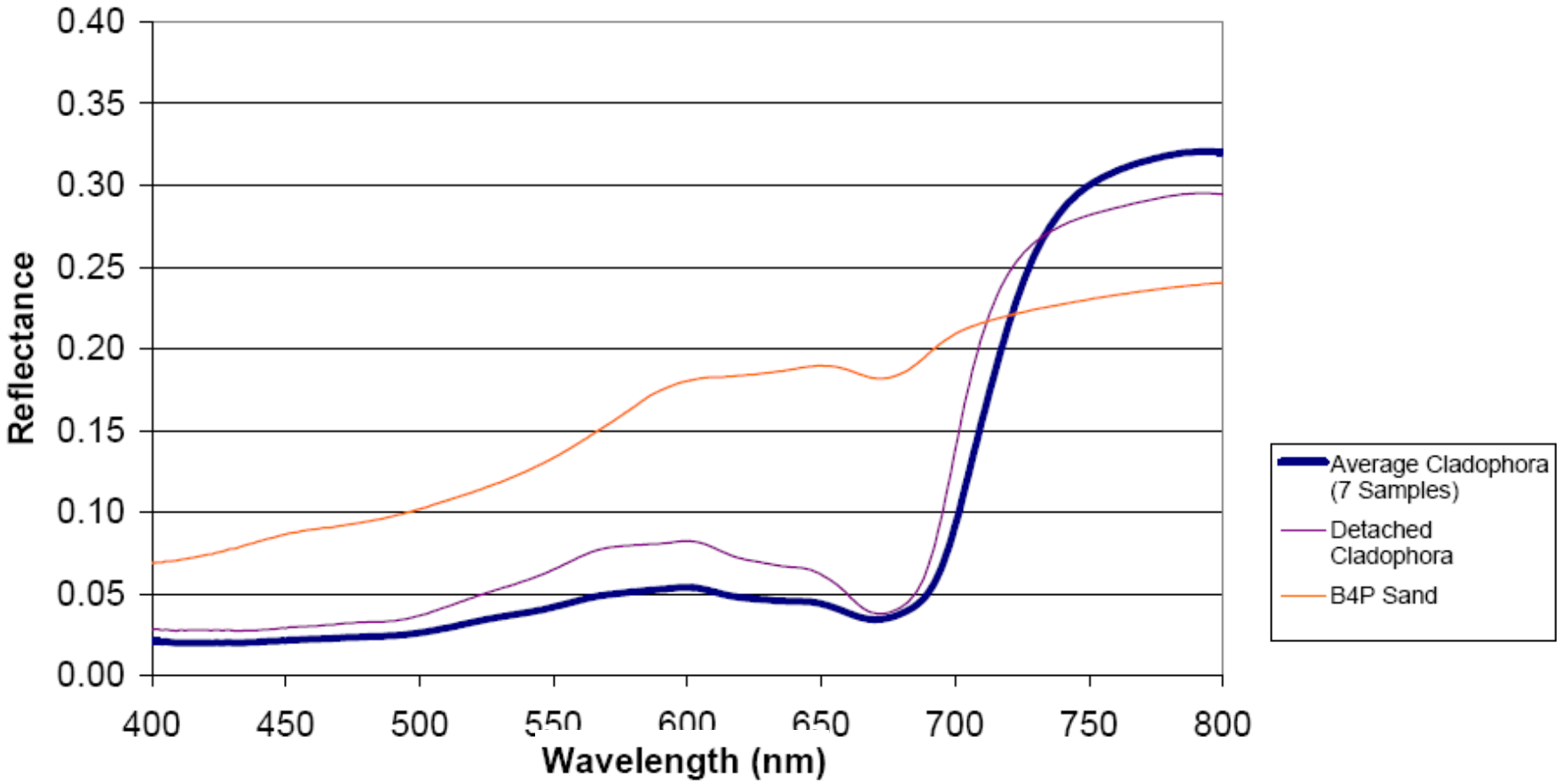
Cladophora Study: 2010 Field Map



Cladophora Study: Initial Observations

- Landsat is a useful sensor to map *Cladophora* in Lake Michigan
- *Cladophora* observed up to 100ft (33 meters) water depth; denser areas <15m
- Average *Cladophora* attached to substrate reflectance in .4 to .7 µm band was approximately 2-5% while sand was 7-20%. Detached Cladophora had reflectance values 2-8%
- *Cladophora* requires hard bottom to grow, zebra mussels can provide that required substrate
- *Cladophora* did colonize on dead zebra mussel-roots attached to shells
- Landsat observed *Cladophora* colonies up to approximately 45-60ft (15-20 meters) depth
- A storm with maximum significant wave height of 2.65 meters (8.45 ft) and maximum winds of 11.2 m/s (22.4 kts) was of sufficient strength to slough or rip *Cladophora* in 8-10 meters (25-30 ft) of water depth off the rocks two days after our 2009 field observations
- Water column at the site was well stratified range of values
  - DO 9-10 (*mg/L*)
  - pH 8.6
  - temp 18.5-19.5 (*℃)*
  - turbidity 0 (*NTU)*
  - conductivity .282 (*mS/cm*)

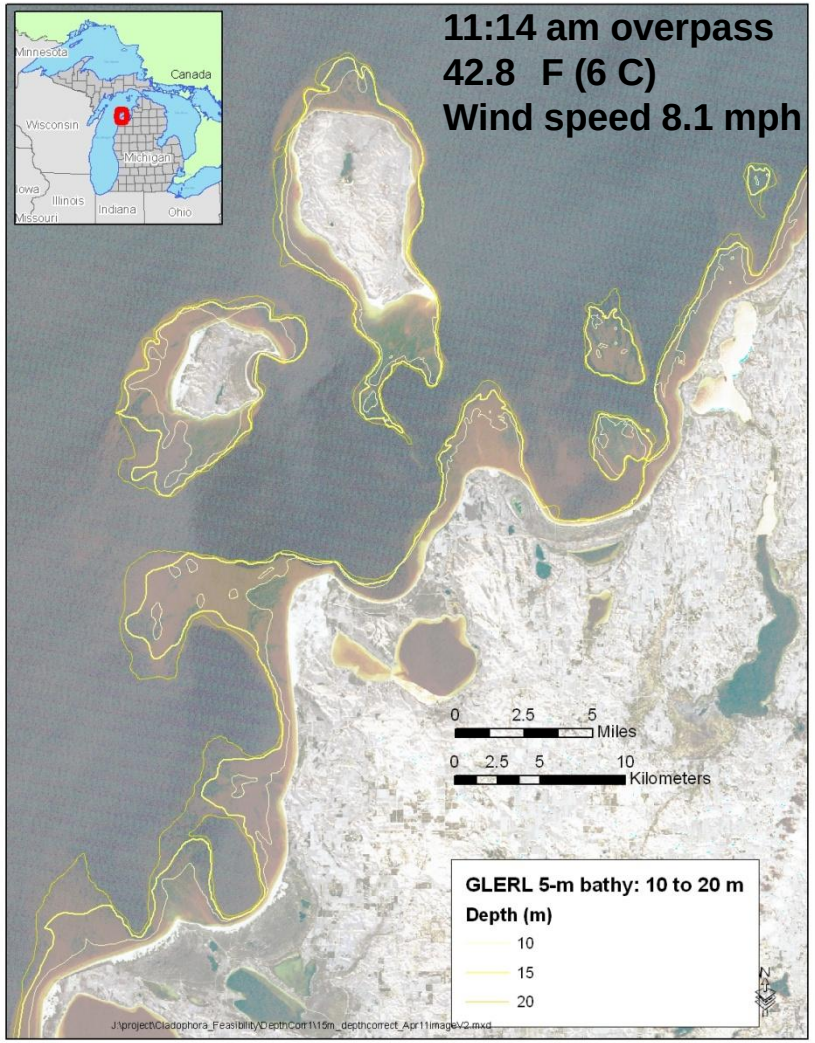
Cladophora Study: Reflectance Results



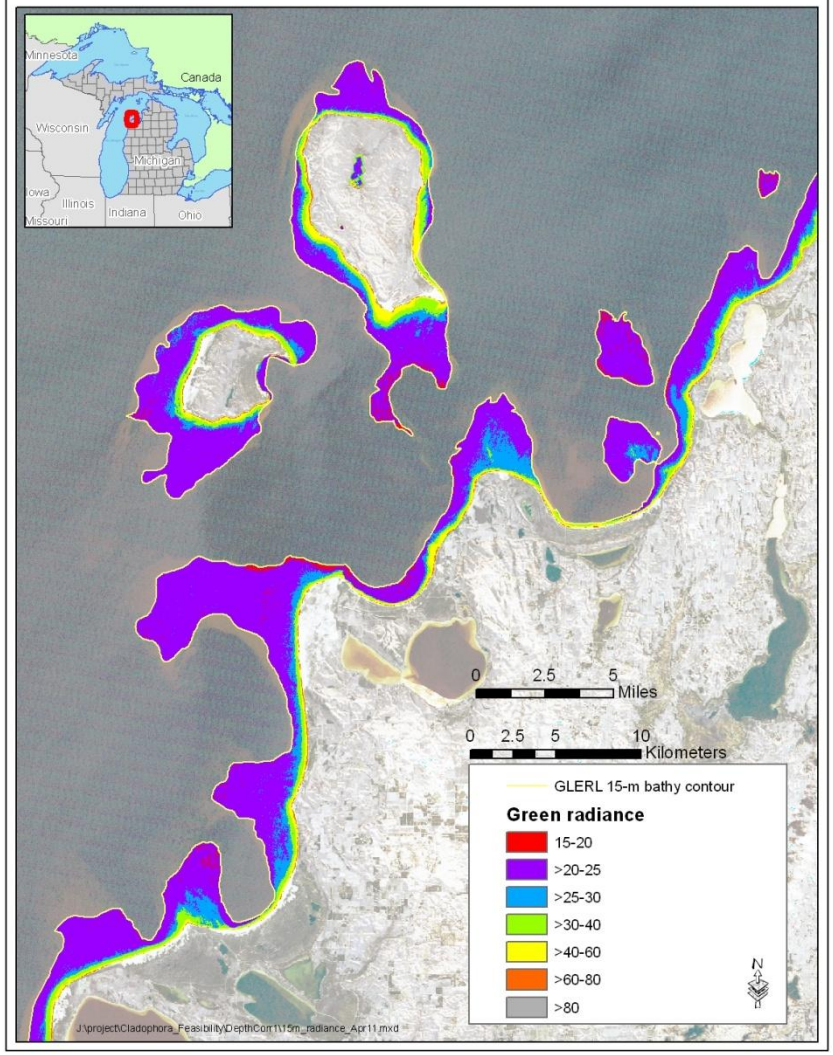
All Sites Averaged
Wet *Cladophora*, Indoors
Bare Fiber, Contact Probe

Cladophora Classification Using Depth-Corrected Landsat 5 Green Band Algorithm for 4/11/2009: Part 1

4/11/2009 Landsat 5 image and 10, 15, and 20 m bathymetric contours

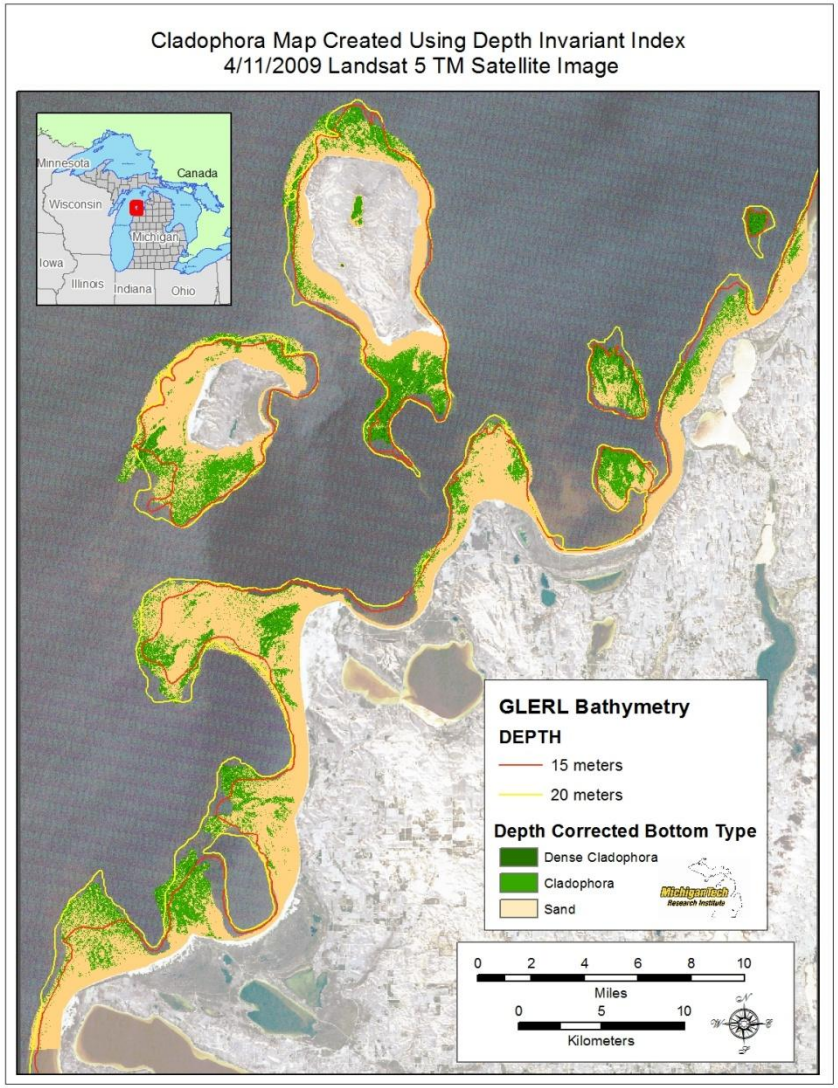


4/11/2009 Landsat 5 green band radiance

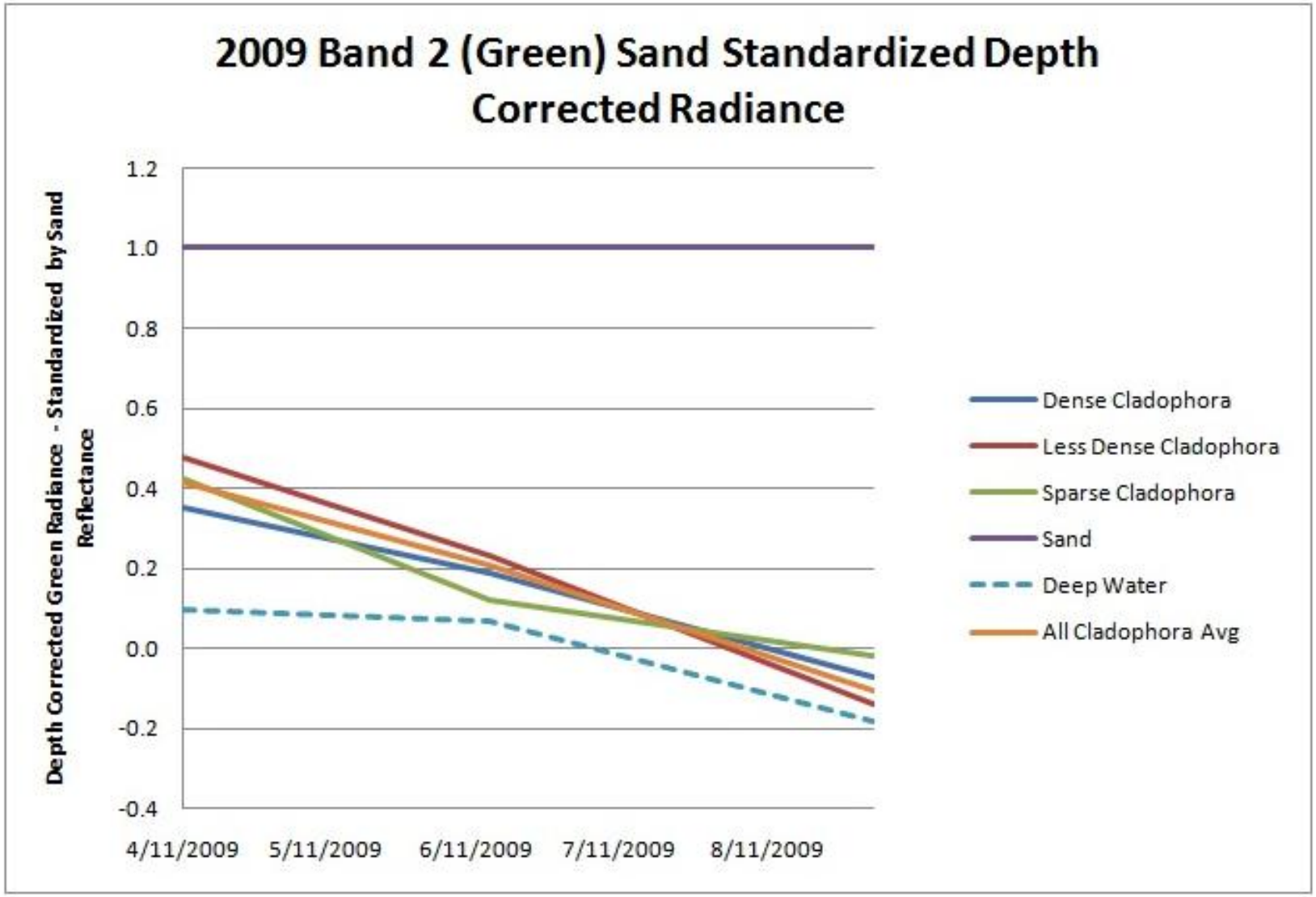


Depth Invariant Index Classification of 4/11/2009 Landsat TM Image

- Classification achieved over 90% accuracy when compared to August 2009 sample sites.
- Both dark and light *Cladophora* is classified.
- Some confusion between dark *Cladophora* and optically deep water.
- With accurate bathymetry, decision rules can be applied to correct confusion.

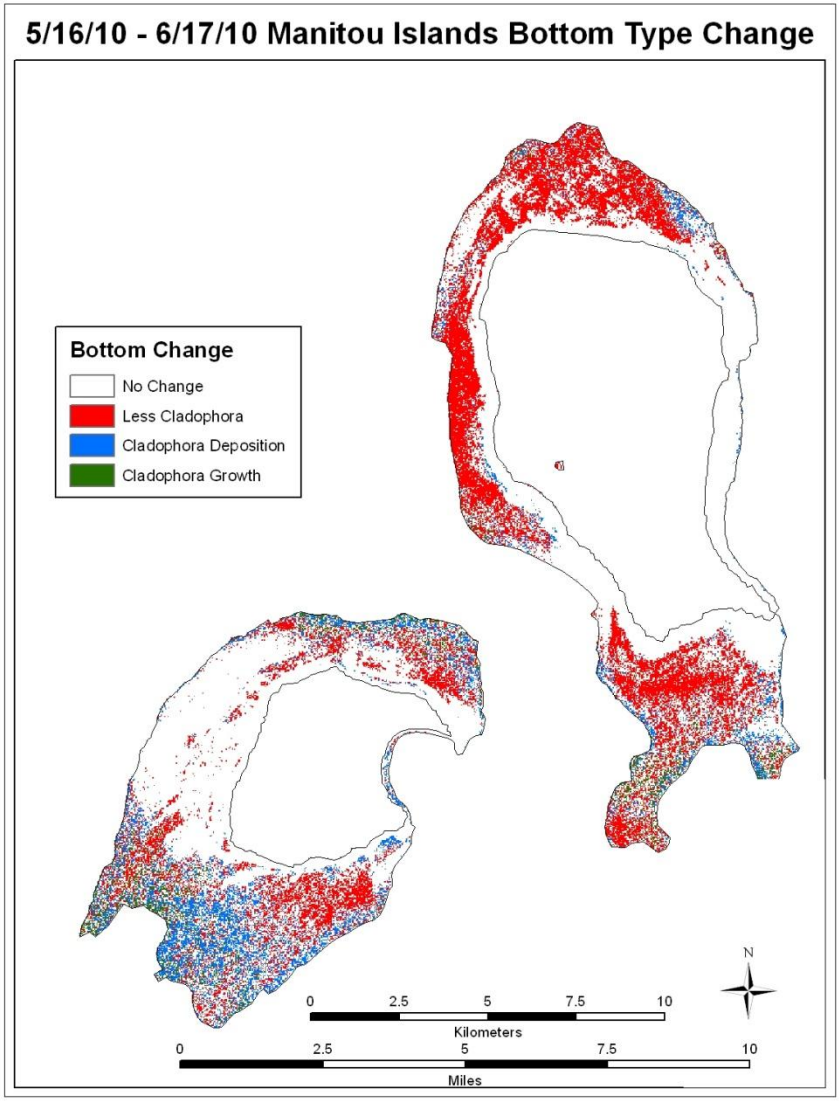


Cladophora Biomass Observations



Cladophora Biomass Calculations

- Have anecdotal evidence of *Cladophora* deposition on North Manitou Island in early June 2010.
- Implies that attached *Cladophora* biomass should be less than previous month.
- Classified pre and post sloughing Landsat Images to examine *Cladophora* extent differences.
- Found areas of extensive *Cladophora* sloughing.
- Observed areas where *Cladophora* was still present but had higher reflectance than pre sloughing.
- Indications that darker *Cladophora* has higher biomass than lighter *Cladophora.*



Cladophora Biomass Estimates

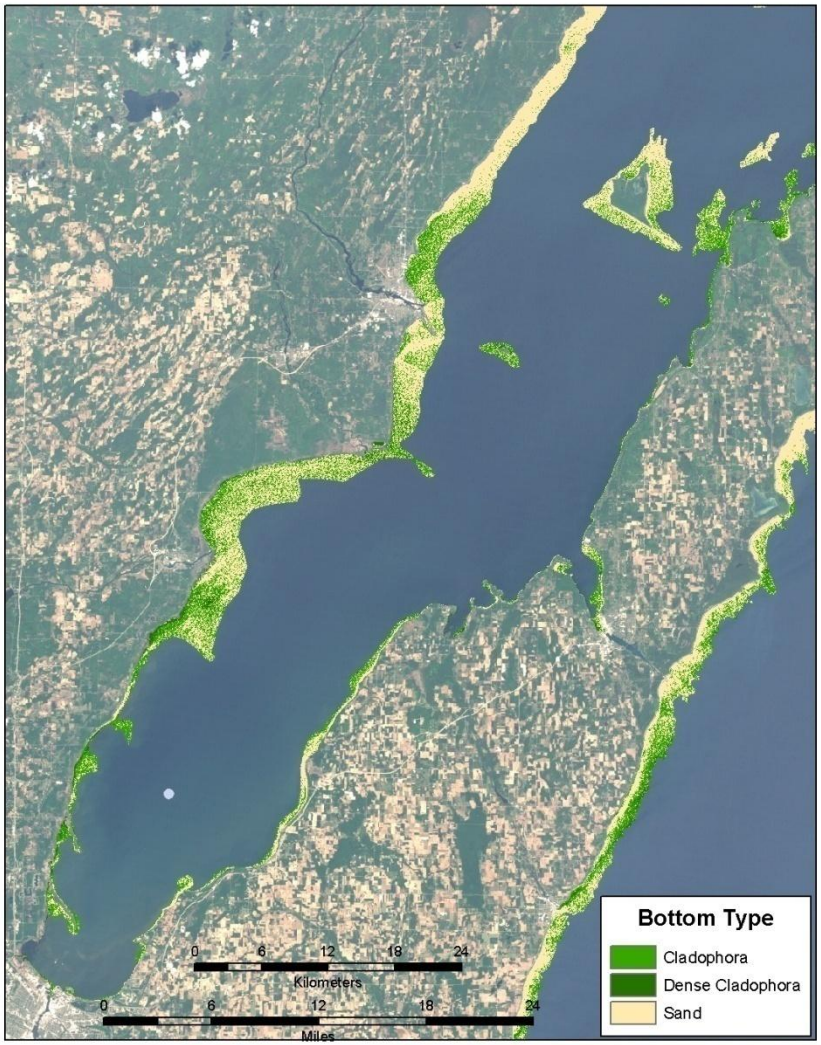
- *Cladophora* dry weights were calculated (grams/sq. meter) from samples collected during 2009-2010 field mission.
- Dry weights were categorized as dense and less dense *Cladophora*.

Bottom Type	Dry Weight Density (g/m^2)	Area (m^2)	Dry Weight Biomass (grams)	Approximate Dry Weight Biomass (tonnes)	Approximate Wet Weight Biomass (tonnes)
Cladophora (Lighter green)	31	98,659,800	3,058,453,800	3058	30585
Dense Cladophora(Darker green)	53	9,802,800	519,548,400	520	5195
Sand	0	223,908,300	0	0	0
				3578	**35780**

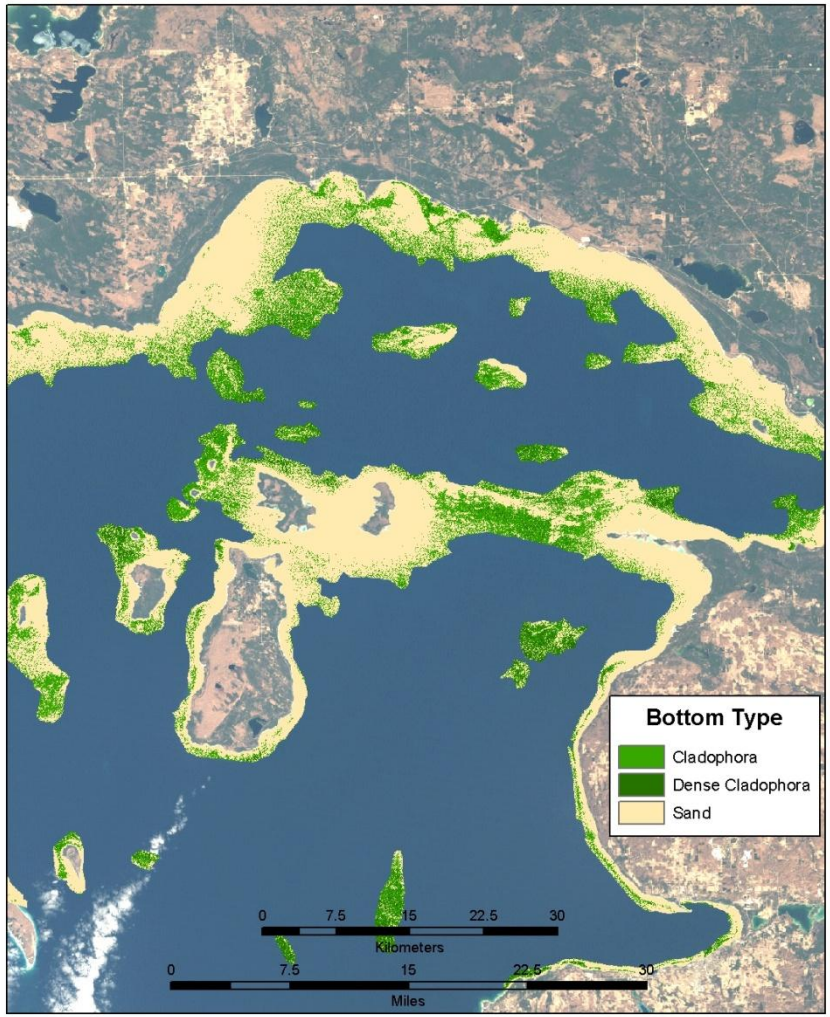
- Area was calculated by summing the number of pixels in each class and multiplying those totals by a single pixel area. (Landsat: 30m x 30m = 900 sq. meters)
- Dry weight biomass was calculated by multiplying the area of each *Cladophora* density class by the corresponding dry weight.
- Wet weight was calculated by multiplying by the standard factor of ten.

2011 Progress
Lake Michigan; Lake Huron Next

Cladophora Extent for Green Bay, Wisconsin -
Landsat 5 TM Image, 6/5/2009

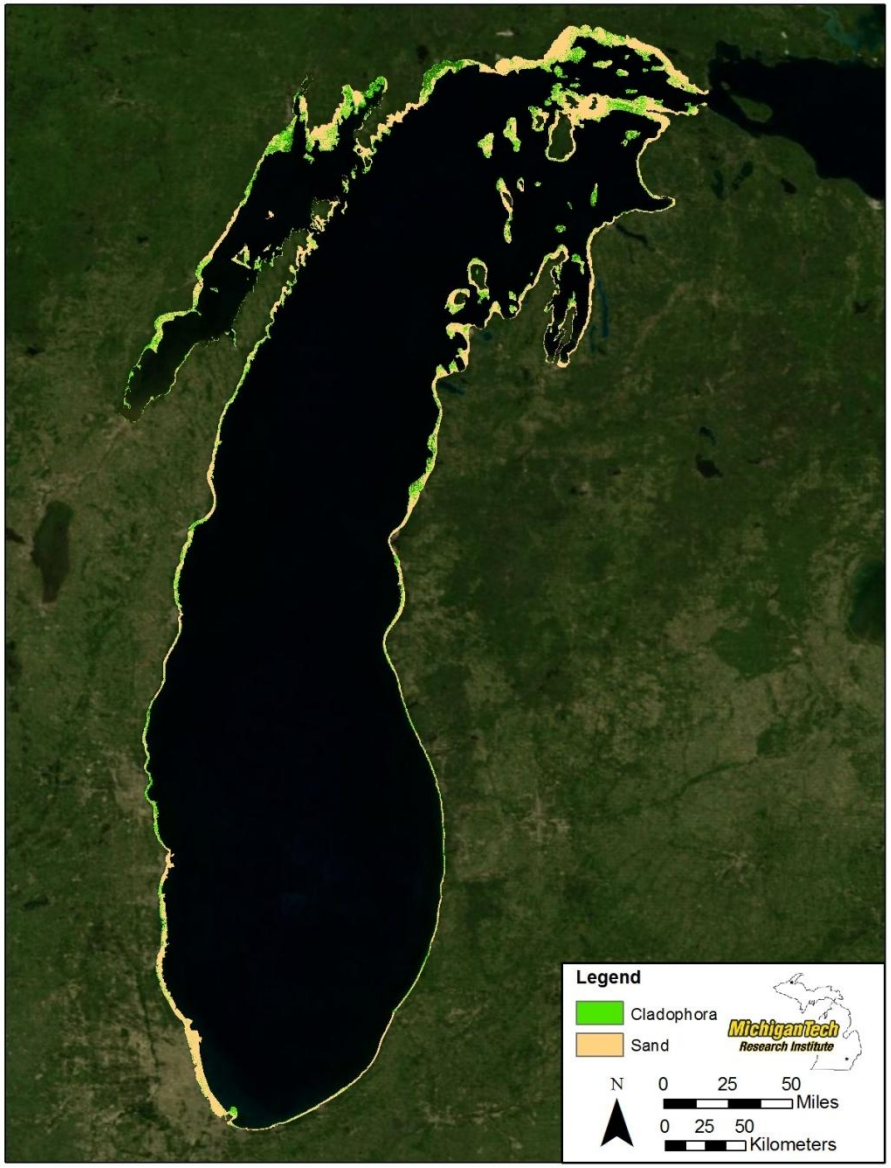


Cladophora Extent for the North Shore of Lake Michigan
Near Naubinway, Michigan -
Landsat 5 TM Image, 3/29/2010

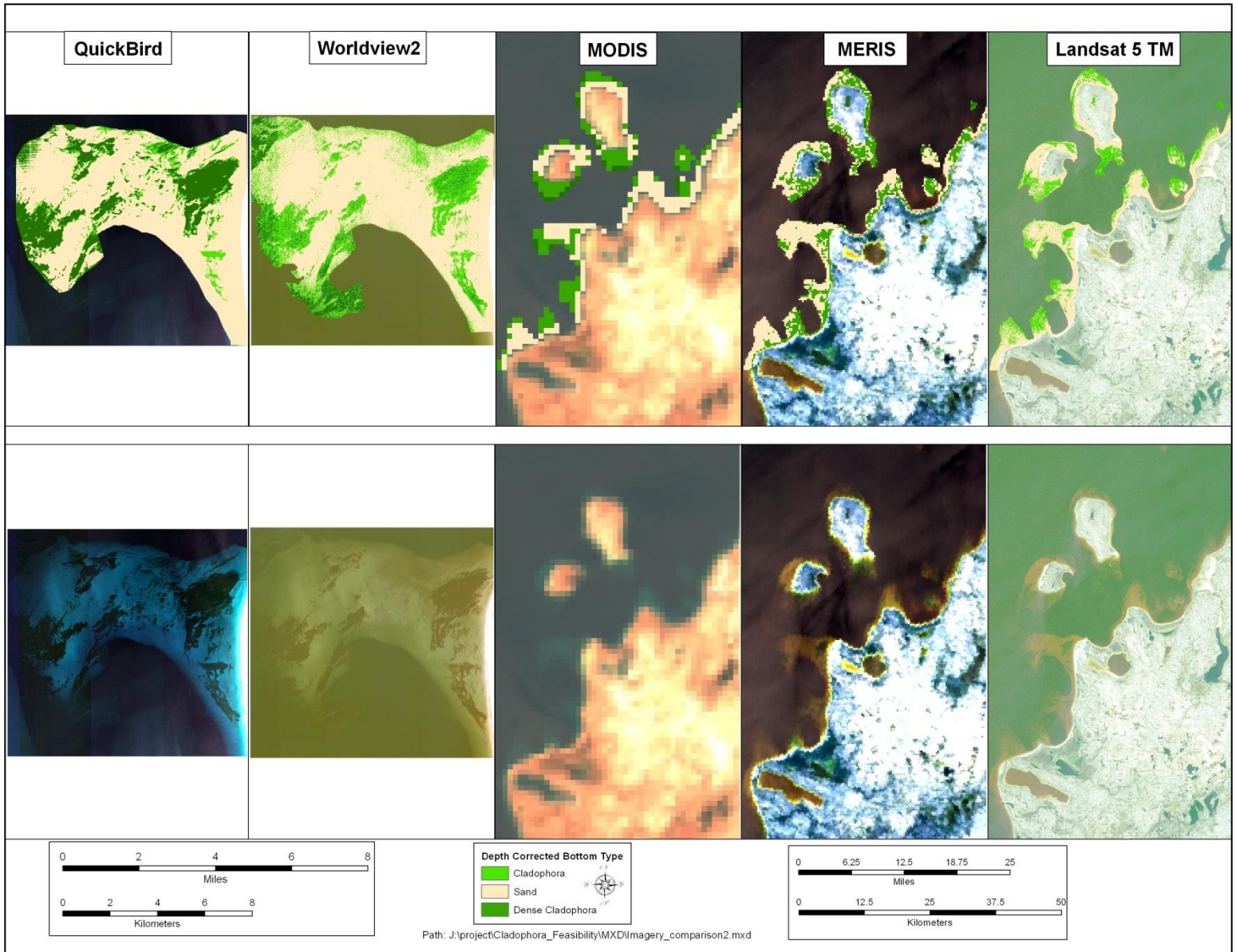


Lake Michigan Example

- In Lake Michigan 32% of the visible bottom consists of *Cladophora* (1530 km^2 out of the 4740 km^2)
- The optical depth varied from 7m to 18m depth

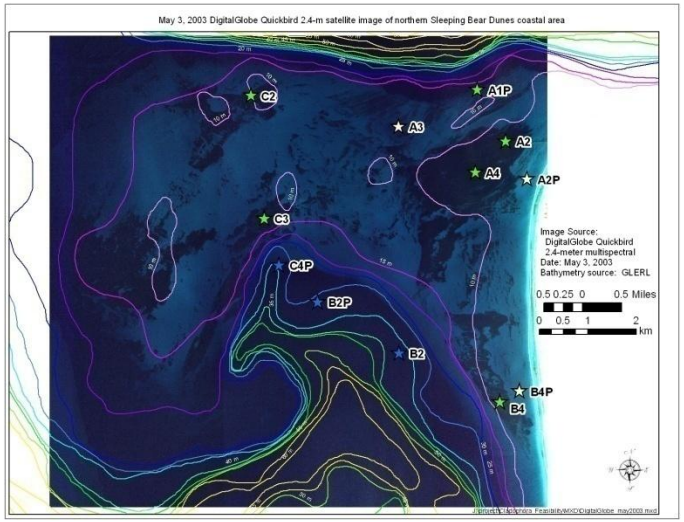


Multi-scale *Cladophora* Mapping Capability

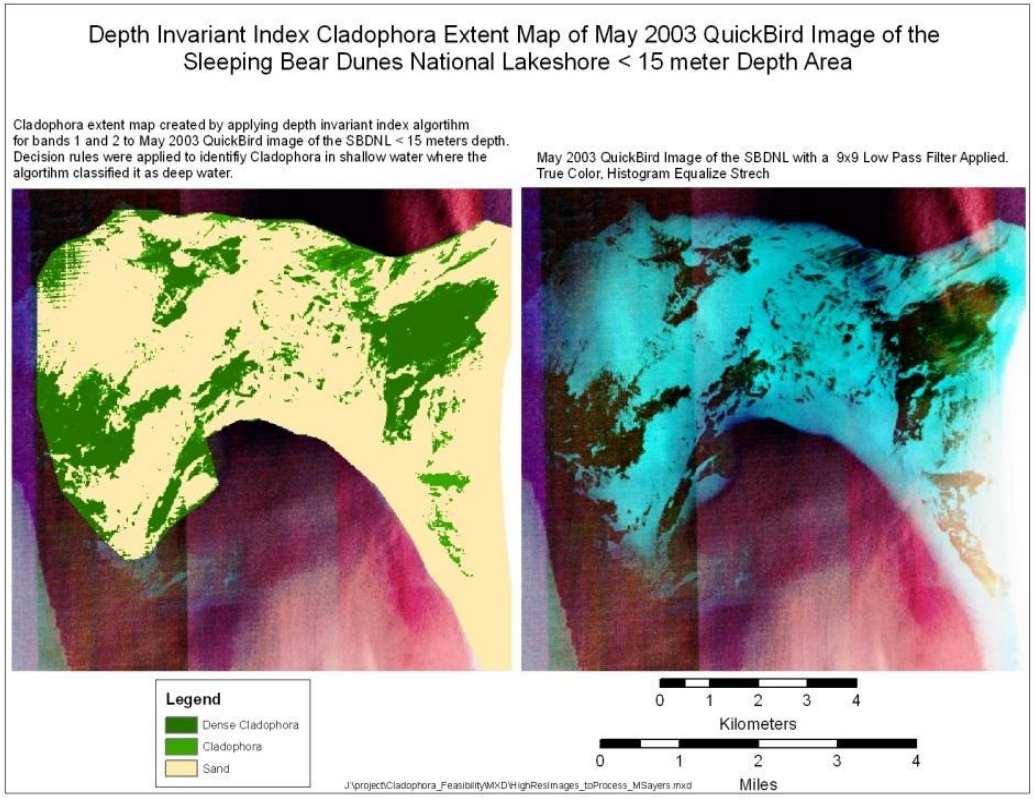


High Resolution Imagery *Cladophora* Mapping

- High resolution imagery (ie. < 5m pixels) allow for much more detailed classifications.

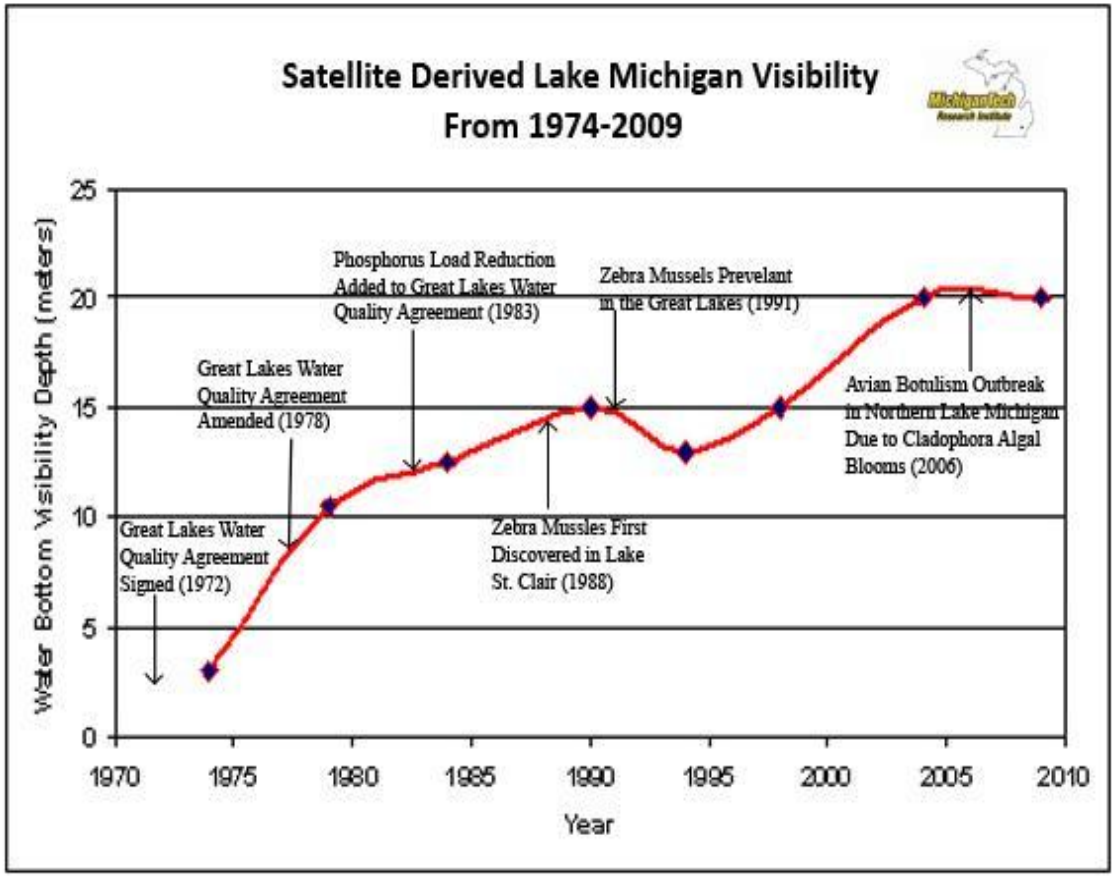


Decision rules were applied to help with classification confusion.



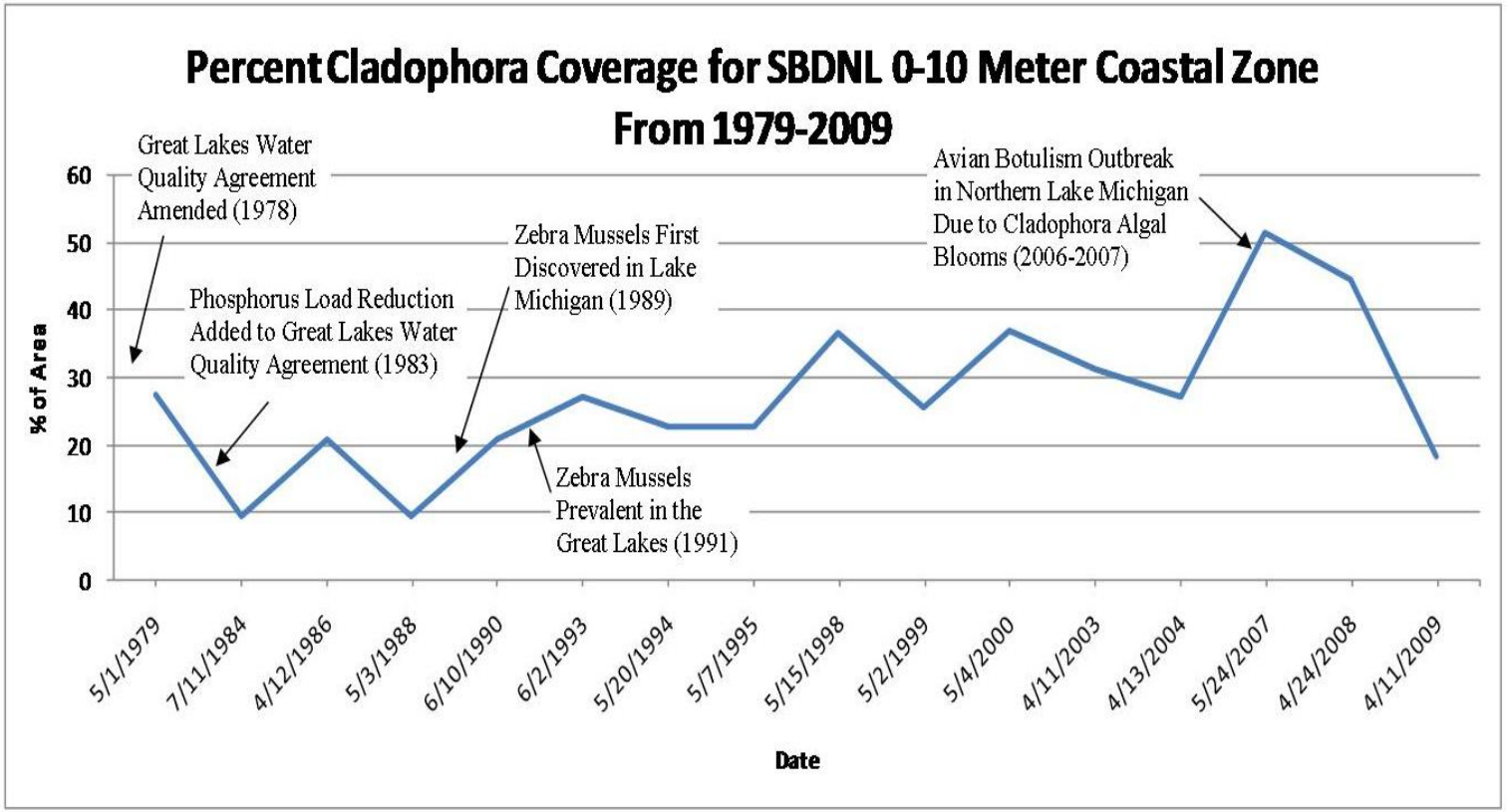
Historical Lake Michigan Water Clarity

- Derived from historical Landsat TM imagery.
- Used depth corrected radiance algorithm for visible channels.
- Water clarity measured historically over Sleeping Bear Dunes National Lakeshore (SBDNL) study site.



Sleeping Bear Dunes National Lakeshore Time Series Analysis

- Total area within 0-10 m depth contours is approximately 165 km^2



Example of Landsat Image Inventory for *Cladophora* Extent & Biomass

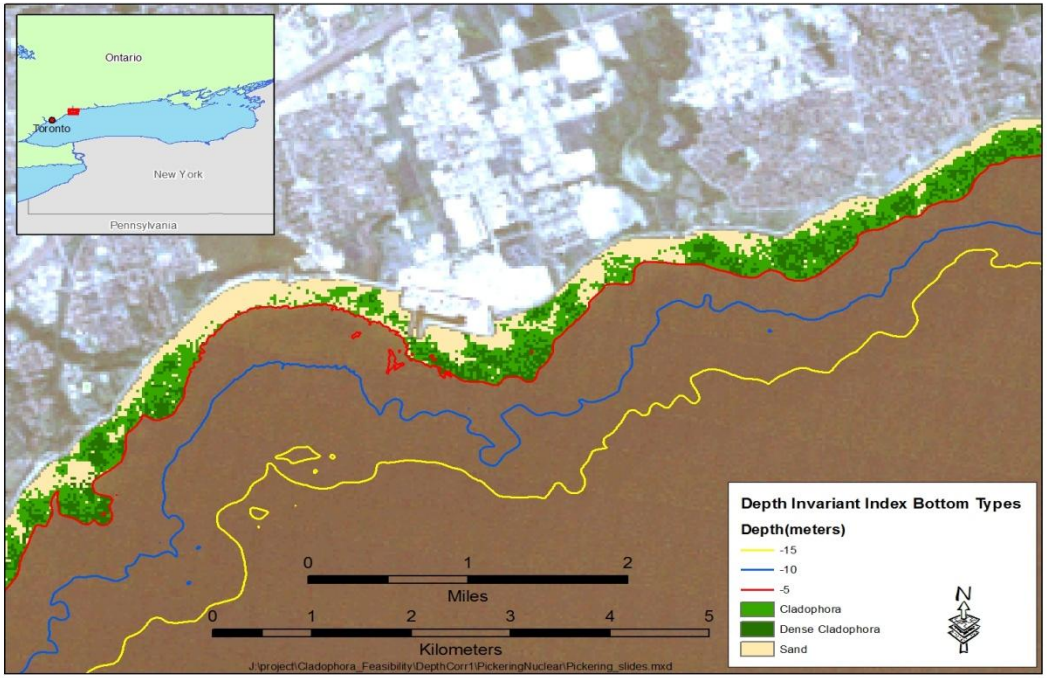
- Usable images need to be cloud free over near-shore areas of interest, good radiometric contrast

Path/Row	p16r29	p16r30	p17r29	p17r30	p17r31	p18r29	p18r30	p18r31	p19r28	p19r29	p19r30	p19r31	p20r28	p20r29
Dates of Overflights	20080414	20080329	20080405	20080405	20080405	20080615	20080412	20080412	20080403	20080403	20080403	20080403	20080410	20080528
	20080430	20080414	20080421	20080421	20080421	20080701	20080428	20080428	20080419	20080419	20080419	20080419	20080426	20090429
	20080516	20080430	20080507	20080507	20080507	20080717	20080514	20080514	20080505	20080505	20080505	20080505	20080512	20090531
	20080601	20080516	20080523	20080523	20080523	20080818	20080530	20080530	20080521	20080521	20080521	20080521	20080528	20090616
	20080617	20080601	20080608	20080608	20080608	20080903	20080615	20080615	20080606	20080606	20080606	20080606	20080613	20090819
	20090401	20080617	20080624	20080624	20080624	20080919	20080701	20080701	20080622	20080622	20080622	20080622	20080629	20080410
	20090417	20090401	20090323	20080710	20080710	20090314	20080717	20090415	20090406	20080724	20080724	20080724	20090413	20080426
	20090503	20090417	20090408	20081030	20090408	20090415	20080818	20090501	20090422	20081012	20090201	20090406	20090429	20080512
	20090519	20090503	20090424	20090323	20090424	20090517	20080903	20090517	20090508	20090406	20090406	20090422	20090515	20080613
	20090604	20090519	20090510	20090408	20090510	20090720	20080919	20090602	20090524	20090422	20090422	20090508	20090531	20080629
	20090620	20090604	20090526	20090424	20090526	20090805	20090314	20090618	20090609	20090508	20090508	20090524	20090616	20100416
	20100404	20090620	20090611	20090510	20090611	20090821	20090415	20100402	20090625	20090524	20090524	20090609	20100416	20100502
	20100420	20100404	20090627	20090526	20090627	20090906	20090501	20100418	20100324	20090609	20090609	20090625	20100502	20100603
	20100506	20100420	20090713	20090611	20090713	20091008	20090517	20100504	20100409	20090625	20090625	20090727	20100518	20100619
	20100522	20100506	20100326	20090627	20100411	20100402	20090602	20100520	20100425	20100324	20100204	20100220	20100603	20100518
	20100607	20100522	20100411	20090915	20100427	20100418	20090618	20100605	20100511	20100409	20100324	20100409	20100619	20090413
	20100623	20100607	20100427	20091017	20100513	20100520	20090704	20100621	20100612	20100425	20100409	20100425		20090515
		20100623	20100513	20091204	20100529	20100707	20090720	20100707	20100628	20100511	20100425	20100511		
			20100529	20100326	20100614	20100504	20090805			20100527	20100511	20100527		
			20100614	20100411	20100630	20100605	20090906			20100612	20100527	20100612		
			20100630	20100427		20100621	20091008			20100628	20100612	20100628		
				20100513		20080412	20100402			20100714	20100628	20100714		
				20100529		20080428	20100418			20100730	20100714			
				20100614		20080514	20100504							
				20100630		20080530	20100520							
				20100716		20090501	20100605							
						20090602	20100621							
						20090618	20100707							
Total Images	17	17	18	18	18	16	16	16	17	18	18	18	16	16
Usable Images	3	8	5	8	3	6	6	4	3	4	3	1	6	5

Alternate Site Application: Pickering Nuclear Power Plant

- Study Site: Nuclear Power Plant at Pickering, Ontario.
- Landsat 5 TM Imagery from 9/17/2007
- Applied Depth Invariant Index algorithm and applied depth decision rule to derive *Cladophora* extent.
- Optical light penetration depth in Lake Ontario is much shallower (~5 m) than observed in Lake Michigan (~20 m).

Cladophora map created using depth invariant index 9/17/2007 Landsat 5 data

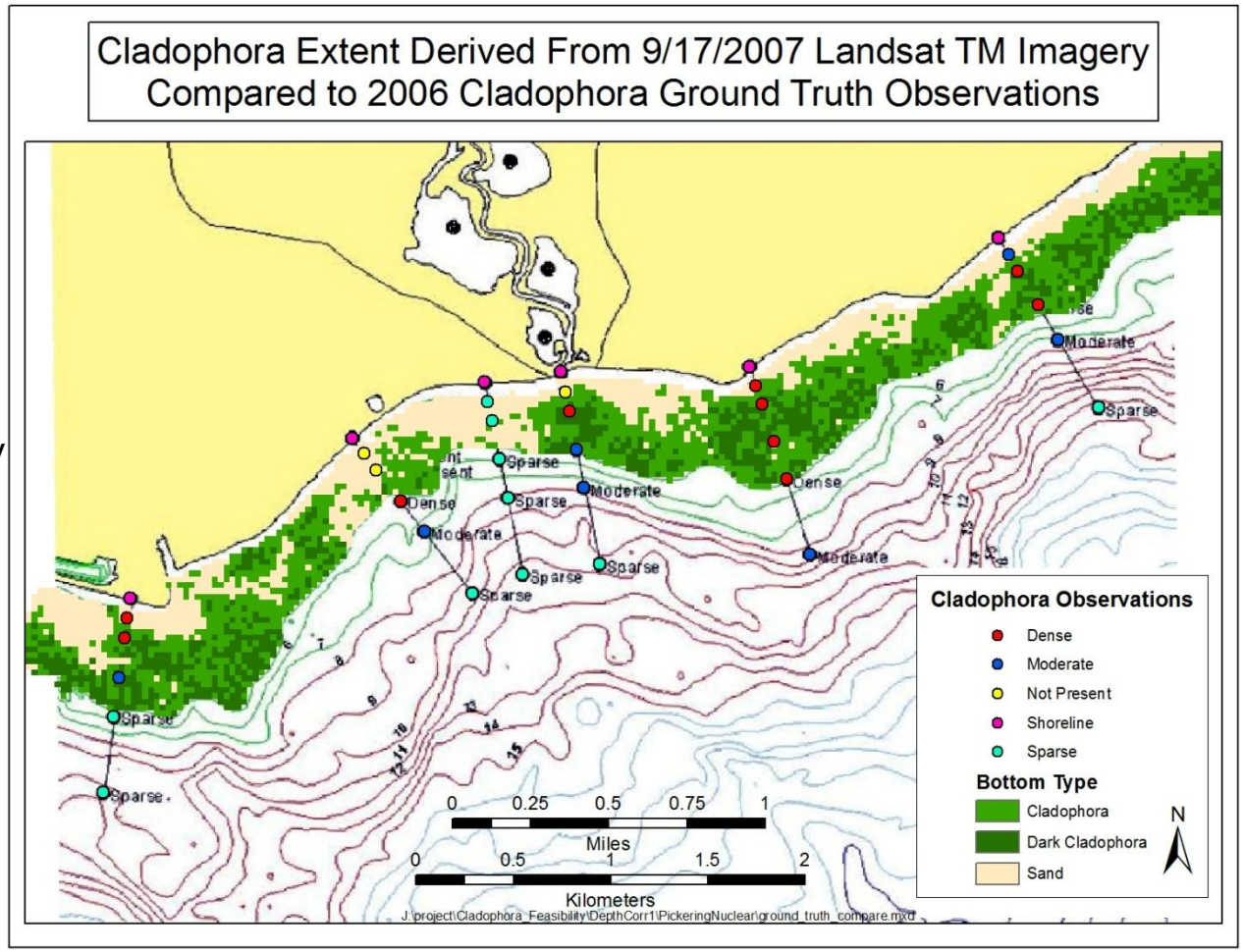


	OPG Quickbird	*OPG Landsat*	*MTRI Landsat*
Primary AOI Biomass (wet weight tonnes)	310	390	316
Regional AOI Biomass (wet weight tonnes)	1331	1833	1539

OPG reported Cladophora biomass vs. MTRI derived biomass

Pickering *Cladophora* Classification Accuracy

- Comparison of *Cladophora* extent derived from 9/17/2007 Landsat imagery with ground truth observations yields positive results.
- The majority of observations agree with corresponding classification pixels.
- Confusion seems to be linked with overall *Cladophora* density and transitional pixels between bottom types.
- Transition error can be associated with the integration of changing bottom type over a 30 meter pixel.
- Further work will be done to relate density and substrate with optical reflectance to minimize density confusion.



Cladophora Study: Next Steps

- Analyze vegetation growing season
  - March through October
  - Extent
  - Biomass
- Additional “lake truth” for better quantification of biomass estimates
- Annual variability
  - May through June imagery
  - 1970s to present
  - Factor in water clarity changes over time
- GLRI – Great Lakes Restoration Initiative
  - Now doing a basin-wide assessment of extent and biomass under GLRI funding (lower 4 Great Lakes)
  - Will be sharing data through MTRI (www.mtri.org), GLOS (www.glos.us), and MichiganView web pages (www.michiganview.org)

Cladophora Study: Concluding Remarks

- Landsat data is a useful tool in mapping *Cladophora* extent and biomass
- Modified Depth Invariant Index algorithm (based on Lyzenga's work) provides robust estimates
- Technique performance is a function of water clarity (secchi disk)
  - Michigan 15-20 meters
  - Ontario 5 meters
- High resolution (~2-3 meter) commercial satellite data provides greater detail, but at increased cost

Funded through NASA ROSES & EPA GLRI

Questions?

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